CH2MHILL®

Kinder Morgan Linnton Terminal – Barrier Wall Extraction System Capture Analysis

PREPARED FOR: Oregon Department of Environmental Quality

PREPARED BY: CH2M HILL

DATE: April 2015

1.0 Introduction

The purpose of this Technical Memorandum is to evaluate the extent of hydraulic capture induced by the groundwater barrier wall and operation of groundwater extraction system consisting of wells EW-1 through EW-7 and MW-19 at the Kinder Morgan Liquids Terminals (KMLT) Linnton Terminal (the Site), located 11400 NW Saint Helens Road in Portland, Oregon (Figure D-1).

The barrier extraction system was designed to achieve the following objectives (CH2M HILL, 2011a):

- Provide active recovery of LNAPL from the landward side of the sheet pile wall

- Prevent groundwater mounding behind the wall

- Provide gradient control for LNAPL migration towards the wells for recovery and subsequent treatment

- Prevent petroleum-contaminated groundwater and LNAPL from migrating around, over or through (in the event of sheet pile defects) the sheet pile barrier and into the Willamette River

- Provide capture of dissolved-phase contaminants that may be migrating towards the Willamette River from the vicinity of MW-9, in the southern portion of the site

The barrier wall and extraction system includes a 216-foot-long, 30-foot deep, impermeable barrier wall and associated hydraulic gradient control system intended to prevent LNAPL migration to the river within the interim action target area identified in the interim action feasibility study (CH2M HILL, 2011b) and shown in Figure D-1. Extraction wells EW-1, EW-2, EW-3, and EW-5 were installed to capture groundwater directly upgradient of the barrier wall; extraction wells EW-6 and EW-7 were installed in 2014 to capture groundwater at the north and south ends of the wall. Extraction well EW-4 was installed at the southeast edge of the Site to capture groundwater coming from the vicinity of MW-9. Details on the barrier wall system are included in CH2M HILL (2011a, 2013a, 2013b, 2014a, and 2014b). Construction completion diagrams for the barrier wall, extraction wells and piezometers are included in Appendix F of the Groundwater Source Control Evaluation (SCE).

The extent of capture was analyzed at the Site in accordance with EPA guidelines (EPA, 2008) through examination of multiple lines of evidence, including:

- Interpretation of groundwater elevations

- Calculations and Analytical Modeling

Tables

D-1 – Parameters for high-water and low-water conditions

D-2a – Flow Rate Calculations – Barrier Wall Vicinity

D-2b – Flow Rate Calculations – EW-4 Vicinity

Figures

2.0 Site Overview

The Conceptual Site Model is discussed in detail in Section 2.5 of the Groundwater Source Control Evaluation (SCE), with cross-sections of the hydrogeology in the vicinity of the barrier wall presented in Figures 2-2, 2-3 and 2-9 of the Groundwater SCE. As shown in Figure D-1, the extent of LNAPL in the barrier wall vicinity extends parallel to the Willamette River from MW-3 to MW-20 and upgradient of the river from the barrier wall and piezometers (PZ-1 to PZ-9) to MW-27 and MW-28. Previous studies (CH2M HILL, 2011b) and ongoing monitoring indicate that NAPL and dissolved groundwater impacts do not extend below the low-conductivity, fine-grained unit underlying the shallow sand in this area. As described in the 2010 LNAPL mobility study at the site (CH2M HILL, 2011b), LNAPL in the vicinity of the barrier wall is not present above residual saturations.

3.0 Hydraulic Parameters

Hydraulic parameters used in the capture analysis are summarized in Table D-1. Values for hydraulic conductivity and saturated thickness of the aquifer were obtained from aquifer step testing conducted in May and September 2014 at the Site as detailed in Appendix C of the Groundwater SCE. Hydraulic parameters in the vicinity of the barrier wall tend to vary with changes in the Willamette river stage. Low-water and high-water conditions at the site tend to persist for extended durations, and are thus assumed to be steady state conditions for purposes of this analysis. To reflect seasonal variations at the Site, representative parameters were selected for the following scenarios:

– 'high-water' conditions (representing conditions typically occurring in summer to late autumn)

– 'low-water' conditions (representing conditions typically occurring in winter to spring)

Pumping rates at individual wells were assessed during the step testing in September 2014 and again during higher river stage in March 2015. In general, pumping rates from the extraction wells on either end of the wall (EW-6 and EW-7) are more than double the pumping rates from the extraction wells positioned behind the barrier wall (i.e., EW-1 through EW-3). As expected, the barrier wall effectively reduces flow to these wells by half.

3.1 Horizontal Gradients:

Well pairs located approximately perpendicular to the direction of horizontal groundwater flow were selected for evaluation of horizontal gradients at the Site including:

- Well pair MW-3 to MW-1, representing near-river conditions
- Well pair MW-11 to PZ-9 representing conditions behind the wall, and
- Well pair MW-9 to PZ-10, representing conditions in the vicinity of EW-4.

Time-series of horizontal flow gradients with respect to the Willamette River stage are shown in Figure D-2. At well pair MW-3 to MW-1, there appears to be a strong tidal influence, with an average gradient of 0.03 ft/ft during periods of low river stage and an average gradient of 0.01 ft/ft during high stage periods. The dataset at well pair MW-11 to PZ-9 shows a similar trend, with gradients ranging between 0.01 and 0.03 ft/ft. At well pair MW-9 to PZ-10 horizontal gradients are consistent over time, averaging 0.02 ft/ft. Periods in 2014 when the system was off during gauging events are shown in Figure D-2. Gradient values selected to represent the horizontal flow gradient toward the barrier wall and EW-4 are shown in Table D-1.

3.2 Vertical Gradients:

Hydrographs at MW-4/4B and MW8/8B in the barrier wall vicinity show consistent and sustained upward gradients (Figure D-3) from the lower sands to the upper sands, indicating that impacted groundwater from the shallow sand is unlikely to migrate down into the lower sand lens in the vicinity of the barrier wall and EW-4 extraction wells.

4.0 Interpretation of Water Levels

Water level elevation contours from January 28, 2015 are presented in Figure D-4. Water levels were gauged after all extraction wells had been running continuously for at least five days and represent mid- to high-water conditions. As shown in Figure D-4, shallow groundwater tends to flow east toward the barrier wall and the Willamette River from upgradient wells MW-11 and MW-9. At the north end of the wall, groundwater flow is predominantly to the south from MW-3 towards EW-6 at the end of the wall. At the south end of the barrier wall, there is an area of groundwater mounding centered over MW-20, with flow from MW-20 to PZ-8 and EW-7.

In the vicinity of EW-4, shallow groundwater flows from MW-9 toward PZ-10 and EW-4. The extent of influence of EW-4 based on water contours is not clear due in part to the proximity of this well to the Site boundary.

Based on these contours the extraction wells behind and adjacent to the barrier wall are capturing flow immediately west and up-gradient of the wall as well as preventing flow around the sides of the barrier wall (Figure D-4a).

Shallow groundwater elevations are at least 12 feet below the top of the barrier wall, indicating flow is unlikely to pass over the top of the barrier wall. Vertical gradients at MW-4/4B and MW-8/8B indicate an upward vertical gradient in the vicinity of the wall. In addition to the upward gradients, the bottom of the wall is keyed into fine grained silts, therefore, flow under the wall is not likely. Grouting was performed in three areas where sheet piles did not reach the underlying silts, as described in detail in the barrier wall construction completion report (CH2M HILL 2013a).

5.0 Calculations and Analytical Modeling

In addition to analysis of water elevation contours, two simple methods of horizontal capture analysis were applied for high-water and low-water conditions at the Site. These methods are described in detail in the USEPA guidance for evaluation of capture zones and pump and treat systems (EPA, 2008).

5.1 Flow and Pumping Rates

The estimated flow rate calculations presented in Table D-2a and D-2b provide an estimate of the pumping rate required to capture the horizontal groundwater flux for the target capture area for a) the area immediately upgradient of the barrier wall, and b) the area upgradient of EW-4.

5.1.1 Barrier Wall Vicinity

Flow rate calculations are presented in Table D-2a for capture of groundwater flux in the vicinity of the barrier wall. For purposes of this analysis, a target capture width of 215 feet was selected (equal to the length of the barrier wall). Other hydraulic parameters were based on values for high- and low-water conditions as detailed in Table D-1. A factor of 1.5 and 2.0 (EPA, 2008) was applied to represent additional flow contributions to the pumping wells, such as recharge from stormwater.

Results indicate the total extraction rate required to capture the flux immediately upgradient of the barrier wall would be approximately 2 to 3 gpm in low-water conditions, and 13 to 18 gpm in high-water conditions. The total combined extraction rates from wells EW-1 to EW-7 and MW-19 are shown in Figure D-5. Prior to installation of EW-6 and EW-7, the total combined extraction rate averaged at least 2 and 3 gpm during low-water conditions. With the initiation of extraction at EW-6 and EW-7 in late October 2015, total system extraction has ranged between 7 and 20 gpm during mid- to high-water conditions, with flow variations due to periodic system maintenance and fluctuations in groundwater elevations. Even subtracting the estimated 0.3 to 0.6 gpm extraction rate from EW-4 (which does not extract groundwater from this target area), the combined extraction rates from wells behind the barrier wall (i.e., EW-1 to EW-3, EW-5 to EW-7, and MW-19) appear to be sufficient in both low- and high-water conditions to capture the horizontal groundwater flux in the barrier wall vicinity.

5.1.2 EW-4 Vicinity

Flow rate calculations are presented in Table D-2b for capture of groundwater flux in the vicinity of EW-4, which was initially installed to provide additional capture of groundwater flow from the vicinity downgradient of MW-9, where PAHs, benzene, dissolved petroleum hydrocarbons, and dissolved metals have been detected (See Section 4.2.1 of the Groundwater SCE). In order to demonstrate capture of flow from MW-9, a target capture width of 70 feet would be required. To demonstrate capture of flow from both MW-9 and MW-8, a target capture width of 125 feet would be required. Other hydraulic parameters were based on values for high- and low-water conditions as detailed in Table D-1. A factor of 1.5 and 2.0 (EPA, 2008) was applied to represent additional flow contributions to the pumping wells, such as flux from the river or upward vertical flux from the lower sand lenses (see Figure D-3).

Results indicate the total extraction rate required to capture the flux coming from the vicinity of MW-9 would be on the order of 0.5 gpm in low-water conditions, and 10 gpm in high-water conditions. Extraction rates at EW-4 under all conditions are estimated to be less than 1 gpm. Based on this analysis, it appears that the pumping rates at EW-4 may be sufficient to capture flux from the vicinity of MW-9 during low-water conditions, but it is unlikely that sufficiently high pumping rates can be achieved during high-water conditions.

5.2 Capture Zone Width

The capture zone width calculations presented in Figures D-6a through D-6d show the estimated outline of the capture zone for individual extraction wells. The calculations include the distance downgradient from the extraction well to the end of the capture zone, and the maximum upgradient capture zone width from the central line of the plume. Hydraulic parameters were based on values in Table D-1. The capture zone width was calculated for both low- and high-water conditions for a) the individual extraction wells on either end of the barrier wall (EW-6 and EW-7) and b) EW-4. The inferred extent of capture for each individual well based on these calculations is shown in Figure D-7, together with the inferred extent of capture based on water level contours.

5.2.1 Barrier Wall Vicinity

The capture zone width calculations for conditions at the ends of the barrier wall (i.e. at EW-6 or EW-7) are presented in Figure D-6a and D-6b. Extraction wells EW-6 and EW-7 were installed within 6 feet from either end of the wall to prevent migration of NAPL and dissolved contaminants around the wall's edge.

Results indicate that under typical low- and high-water conditions, EW-6 and EW-7 will have a half-capture width of between 24 and 80 feet, with a stagnation point approximately eight to 26 feet downgradient from the wells. Based on these estimates, the capture zone should be sufficient to capture groundwater at the ends of the barrier wall.

5.2.2 EW-4 Vicinity

The capture zone width calculations for conditions in the vicinity of EW-4 are presented in Figures D-6c and D-6d. Results indicate that under typical low- and high-water conditions, EW-4 will have a half-capture width of between four and 36 feet, with a stagnation point approximately one to 11 feet downgradient of the well. Capture is more extensive during low-water conditions, when there is less overall flux through the aquifer. The capture width estimates indicate that the extent of the capture zone from EW-4 may be sufficient to capture flow from MW-9 during low-water conditions, but that capture is less likely during high-water conditions.

Dissolved concentrations and LNAPL thicknesses in riverside wells are typically higher during low-water periods, therefore, it is advantageous that the extent of capture is greater during periods of lower water levels.

6.0 Summary and Conclusions

- Water levels demonstrate capture upgradient of barrier wall, north to MW-3, and south to MW-20 in January 2015

- A comparison of estimated flow rate required to capture flow in barrier wall vicinity and actual extraction rates demonstrates that the system is capturing adequate flow behind the wall

- Analytical calculations of capture zone geometry (stagnation point, half-capture zone width) reinforce interpretation of capture from water levels and flow rates for the barrier wall vicinity

- During low-water conditions, pumping at EW-4 may be sufficient to capture flow from MW-9

- Capture around MW-22 and MW-8 will continue to be evaluated

- Continue monitoring fluid levels and review capture semi-annually

7.0 References

CH2M HILL, 2011a. *Interim Action Basis of Design – Barrier Wall System*, Kinder Morgan Linnton Terminal. July 14.

CH2M HILL. 2011b*. Interim Action Feasibility Study,* Kinder Morgan Linnton Terminal. March 17.

CH2M HILL. 2013a. *Interim Action Barrier Wall System-Construction Completion Report, Kinder Morgan Linnton Terminal. December 13*.

CH2M HILL, 2013b. *Extraction Well and Piezometer Installation Report,* Kinder Morgan Linnton Terminal. July 22.

CH2M HILL, 2014a. *Extraction Well Installation and Redevelopment Installation Work Plan,* Kinder Morgan Linnton Terminal. August 19.

CH2M HILL, 2014b. *Extraction Well Installation and Redevelopment Installation Report,* Kinder Morgan Linnton Terminal. November 24.

United State Environmental Protection Agency (EPA), 2008. *A Systematic Approach for Evaluation of Capture Zones and Pump and Treat Systems*. Final Project Report. EPA 600/R-08/003. January.

TABLE D-1

Parameters for High-water and Low-water Conditions

Kinder Morgan Liquid Terminals, Linnton Terminal

SCENARIO - EW-6 or EW-7 (Ends of Barrier Wall)

Parameter	Low-water	High-water	Source Reference
Extraction Rate (Q in gpm)	1	2	[1]; March 2015 flow testing conducted by Antea
Hydraulic Conductivity (K in ft/dy)	4	40	[1]
Saturated Thickness (b in ft)	10	20	[1]
Horiz Hyd Grad (i in ft/ft)	0.03	0.01	Figure D-2

SCENARIO - EW-4

Parameter	Low-water	High-water	Source
Extraction Rate (Q in gpm)	0.3	0.6	[1]
Hydraulic Conductivity (K in ft/dy)	1	10	[1]
Saturated Thickness (b in ft)	10	20	[1]
Horiz Hyd Grad (i in ft/ft)	0.02	0.02	Figure D-2

References:

[1] Step Drawdown Testing Results are presented in Appendix C of the *Groundwater and Bank Soil Source Control Evaluation Report, Kinder Morgan Linnton Terminal*

TABLE D-2a
Flow Rate Calculations - Barrier Wall Vicinity
Kinder Morgan Liquid Terminals, Linnton Terminal

			Factor = 1.5		Factor = 2	
Estimated Flow Rate Calculation Q = K*(b*w)*i*factor			Low-water Conditions	High-water Conditions	Low-water Conditions	High-water Conditions
K	Conductivity	ft/day	4	40	4	40
b	thickness	ft	10	20	10	20
w	target capture width (behind barrier wall)	ft	215	215	215	215
i	horizontal flow gradient	ft/ft	0.03	0.01	0.03	0.01
factor	factor ranging from 1.0 to 2.0	-	1.5	1.5	2	2
Q	Extraction rate required to capture groundwater flux in target capture zone	cubic ft per day	387	2580	516	3440
Q	Extraction rate required to capture groundwater flux in target capture zone	gpm	2	13	3	18

NOTES: 1 cubic ft = 7.48052 US gallons

Estimated Flow Rate Calculation

Assumptions:
- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- no other sources of water introduced to aquifer due to extraction (e.g., from rivers or leakage from above or below)

$$Q = K \cdot (b \cdot w) \cdot i \cdot factor$$

(must use consistent units, such as "ft" for distance and "day" for time)

Where:
Q = extraction rate
K = hydraulic conductivity
b = saturated thickness
w = plume width
i = regional (i.e., without remedy pumping) hydraulic gradient
$factor$ = "rule of thumb" is 1.5 to 2.0, intended to account for other contributions to the pumping well such as flux from a river or induced vertical flow from other stratigraphic unit

Reference: United State Environmental Protection Agency (EPA), 2008. A Systematic Approach for Evaluation of Capture Zones and Pump and Treat Systems. Final Project Report. EPA 600/R-08/003. January, 2008.

TABLE D-2b
Flow Rate Calculations - EW-4 Vicinity
Kinder Morgan Liquid Terminals, Linnton Terminal

Estimated Flow Rate Calculation Q = K*(b*w)*i*factor			Factor = 1.5		Factor = 2	
			Low-water Conditions	High-water Conditions	Low-water Conditions	High-water Conditions
K	Conductivity	ft/day	4	40	4	40
b	thickness	ft	10	20	10	20
w	target capture width (extend to MW-9)	ft	70	70	70	70
i	horizontal flow gradient	ft/ft	0.02	0.02	0.02	0.02
factor	factor ranging from 1.0 to 2.0	-	1.5	1.5	2	2
Q	Extraction rate required to capture groundwater flux in target capture zone	cubic ft per day	84	1680	112	2240
Q	Extraction rate required to capture groundwater flux in target capture zone	gpm	0.4	9	0.6	12

NOTES: 1 cubic ft = 7.48052 US gallons

Estimated Flow Rate Calculation

Assumptions:
- homogeneous, isotropic, confined aquifer of infinite extent
- uniform aquifer thickness
- fully penetrating extraction well(s)
- uniform regional horizontal hydraulic gradient
- steady-state flow
- negligible vertical gradient
- no net recharge, or net recharge is accounted for in regional hydraulic gradient
- no other sources of water introduced to aquifer due to extraction (e.g., from rivers or leakage from above or below)

$$Q = K \cdot (b \cdot w) \cdot i \cdot factor$$

(must use consistent units, such as "ft" for distance and "day" for time)

Where:
Q = extraction rate
K = hydraulic conductivity
b = saturated thickness
w = plume width
i = regional (i.e., without remedy pumping) hydraulic gradient
$factor$ = "rule of thumb" is 1.5 to 2.0, intended to account for other contributions to the pumping well such as flux from a river or induced vertical flow from other stratigraphic unit
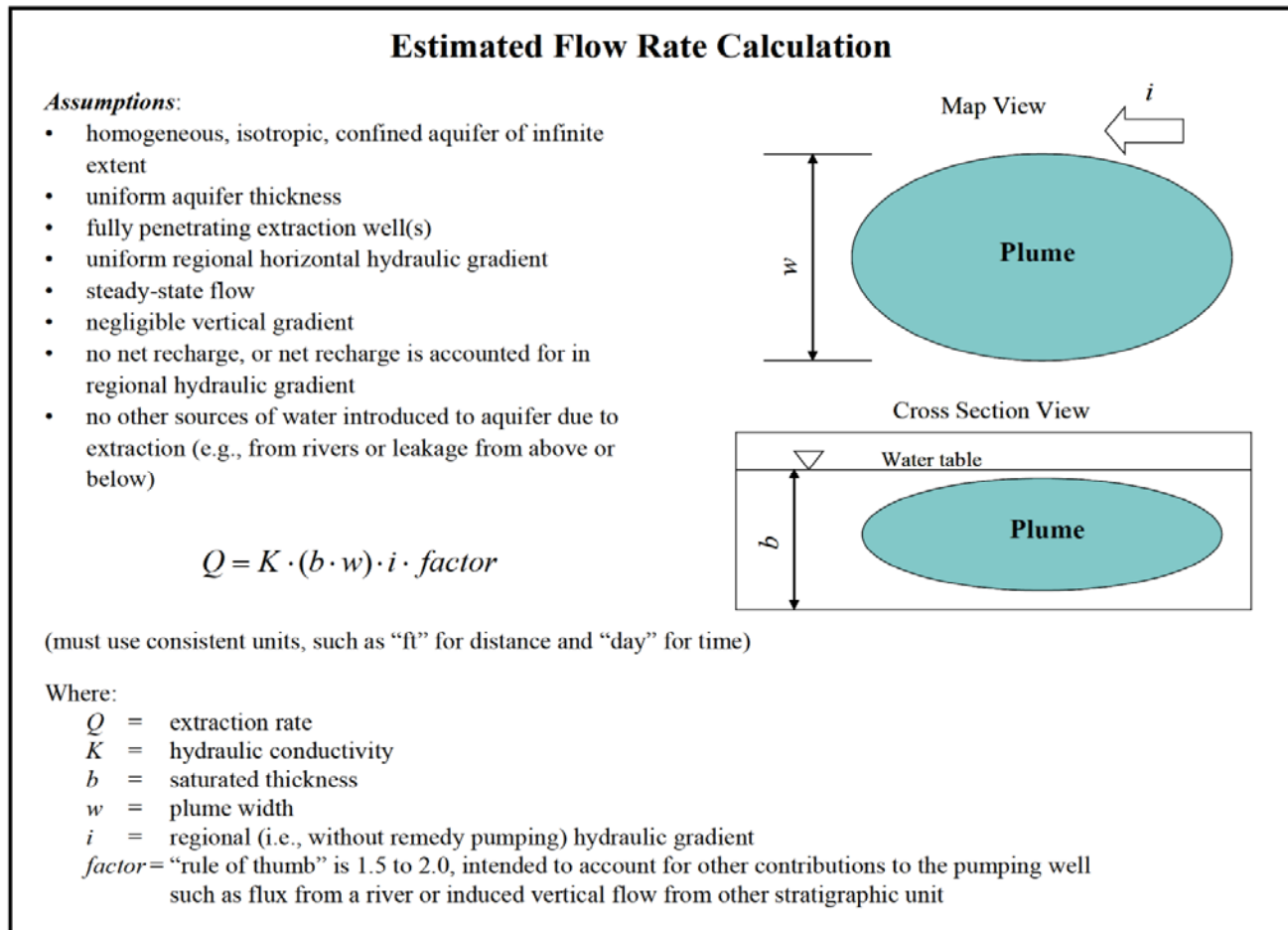
Reference: United State Environmental Protection Agency (EPA), 2008. A Systematic Approach for Evaluation of Capture Zones and Pump and Treat Systems. Final Project Report. EPA 600/R-08/003. January, 2008.
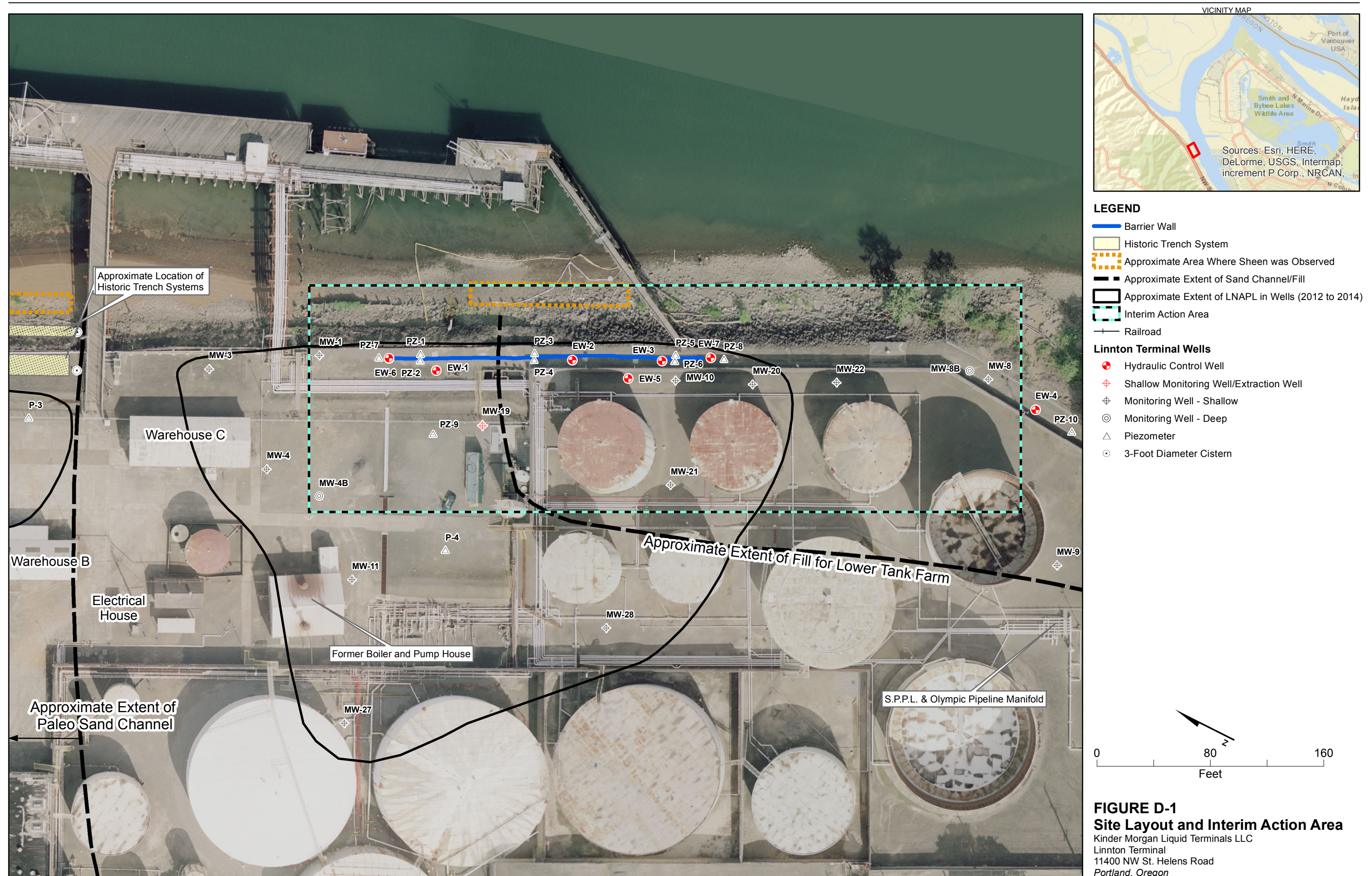
VICINITY MAP

Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN,

LEGEND

— Barrier Wall
▨ Historic Trench System
⬚ Approximate Area Where Sheen was Observed
▬ ▬ Approximate Extent of Sand Channel/Fill
▭ Approximate Extent of LNAPL in Wells (2012 to 2014)
⬚ Interim Action Area
+ Railroad

Linnton Terminal Wells

◉ Hydraulic Control Well
⊕ Shallow Monitoring Well/Extraction Well
⊕ Monitoring Well - Shallow
◎ Monitoring Well - Deep
△ Piezometer
⊙ 3-Foot Diameter Cistern

Approximate Location of Historic Trench Systems

MW-3
MW-1 PZ-7 PZ-1   PZ-3 EW-2   EW-3   PZ-5 EW-7 PZ-8
EW-6 PZ-2 EW-1   PZ-4   PZ-6   MW-20   MW-22   MW-8B   MW-8
P-3   EW-5   MW-10   EW-4
                                                                                                                PZ-10
MW-19
Warehouse C
PZ-9
MW-4
MW-21
MW-4B

Approximate Extent of Fill for Lower Tank Farm

Warehouse B
P-4
Electrical House
MW-11
MW-9

Former Boiler and Pump House

MW-28

Approximate Extent of Paleo Sand Channel

MW-27

S.P.P.L. & Olympic Pipeline Manifold

0   80   160
Feet

FIGURE D-1
Site Layout and Interim Action Area
Kinder Morgan Liquid Terminals LLC
Linnton Terminal
11400 NW St. Helens Road
Portland, Oregon

<ACP> \\rosa\Proj\HoneywellInc\326958\GIS\MapFiles\2015\FigureD-1_SiteLayout&IAA_v3.mxd JSAGER 8/21/2015 3:50:38 AM</ACP>
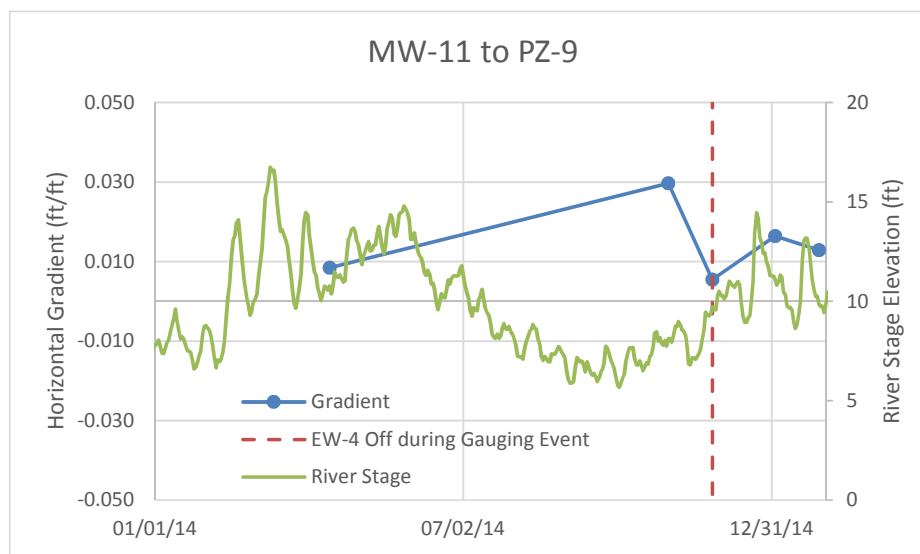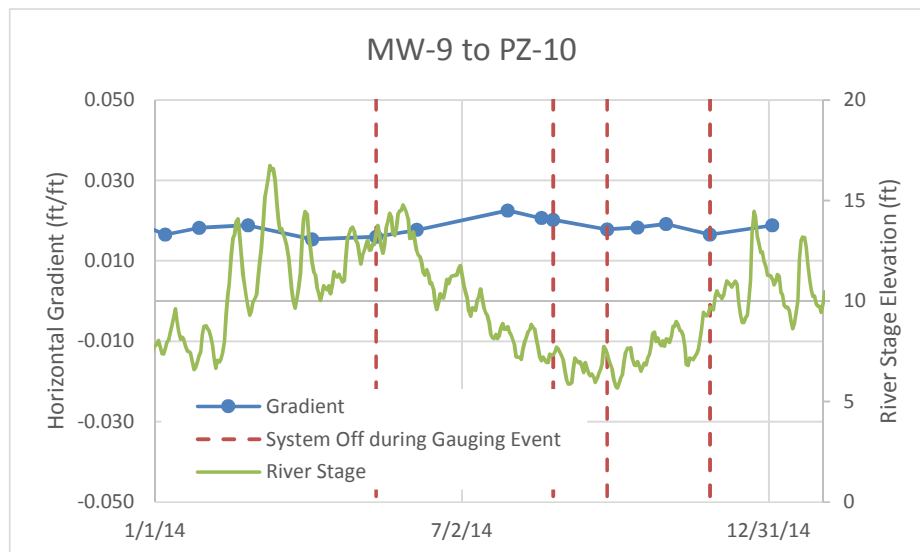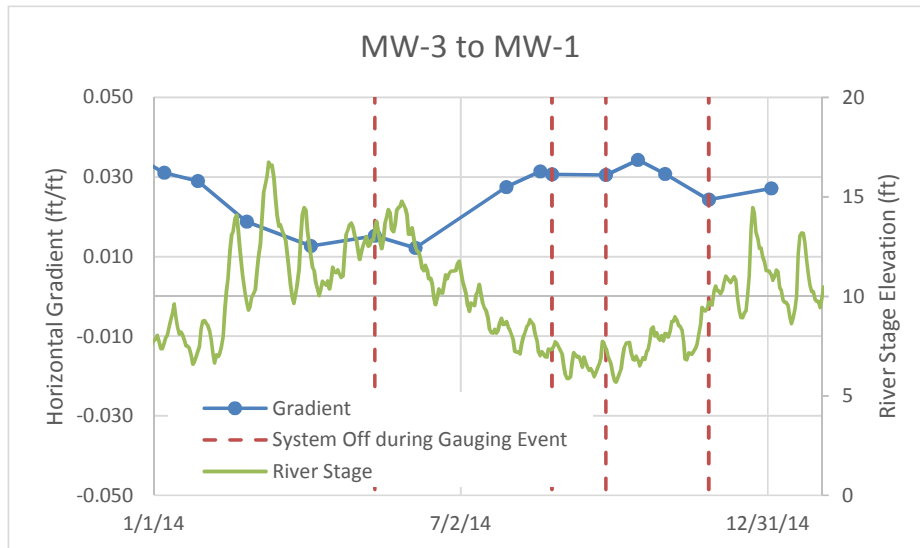
CH2MHILL

Figure D-2
Horizontal Gradient vs. River Stage
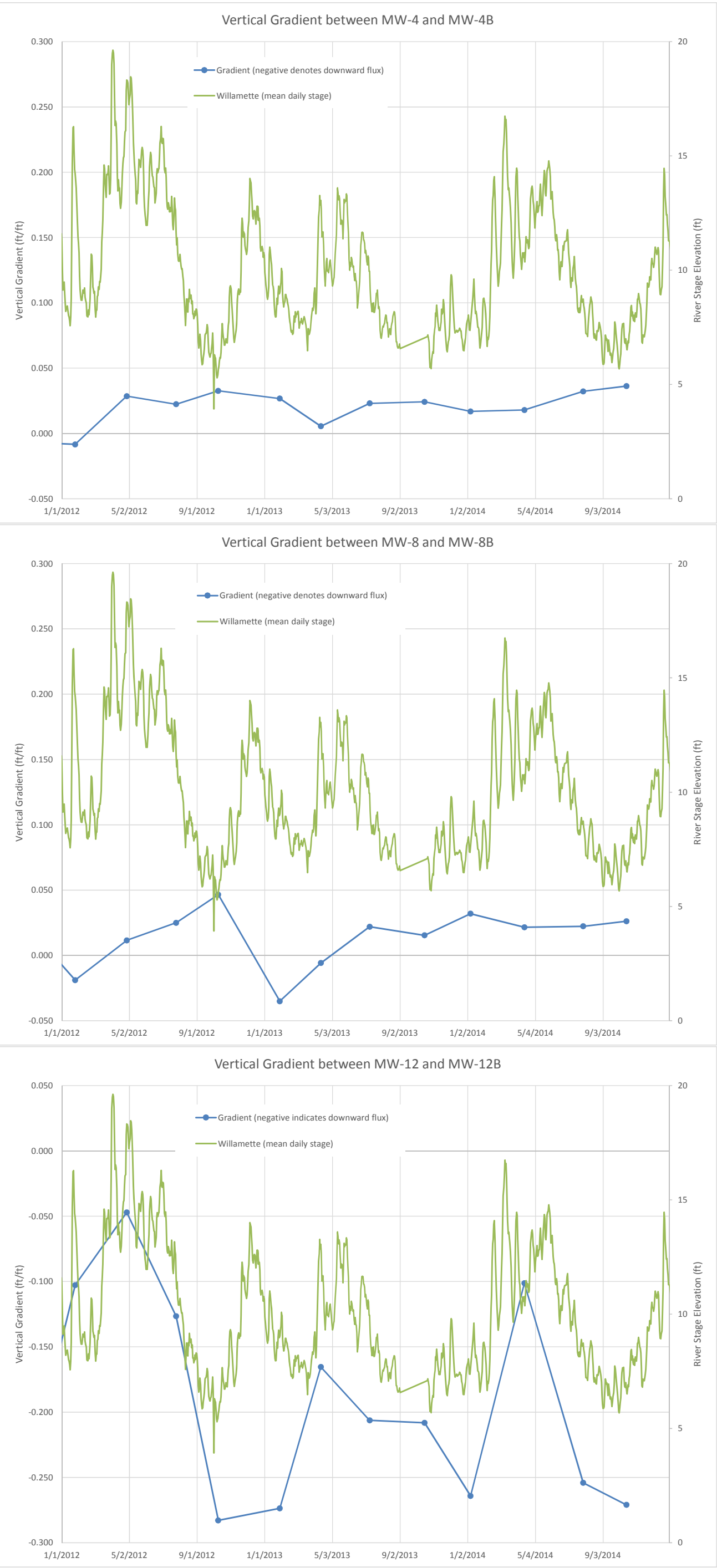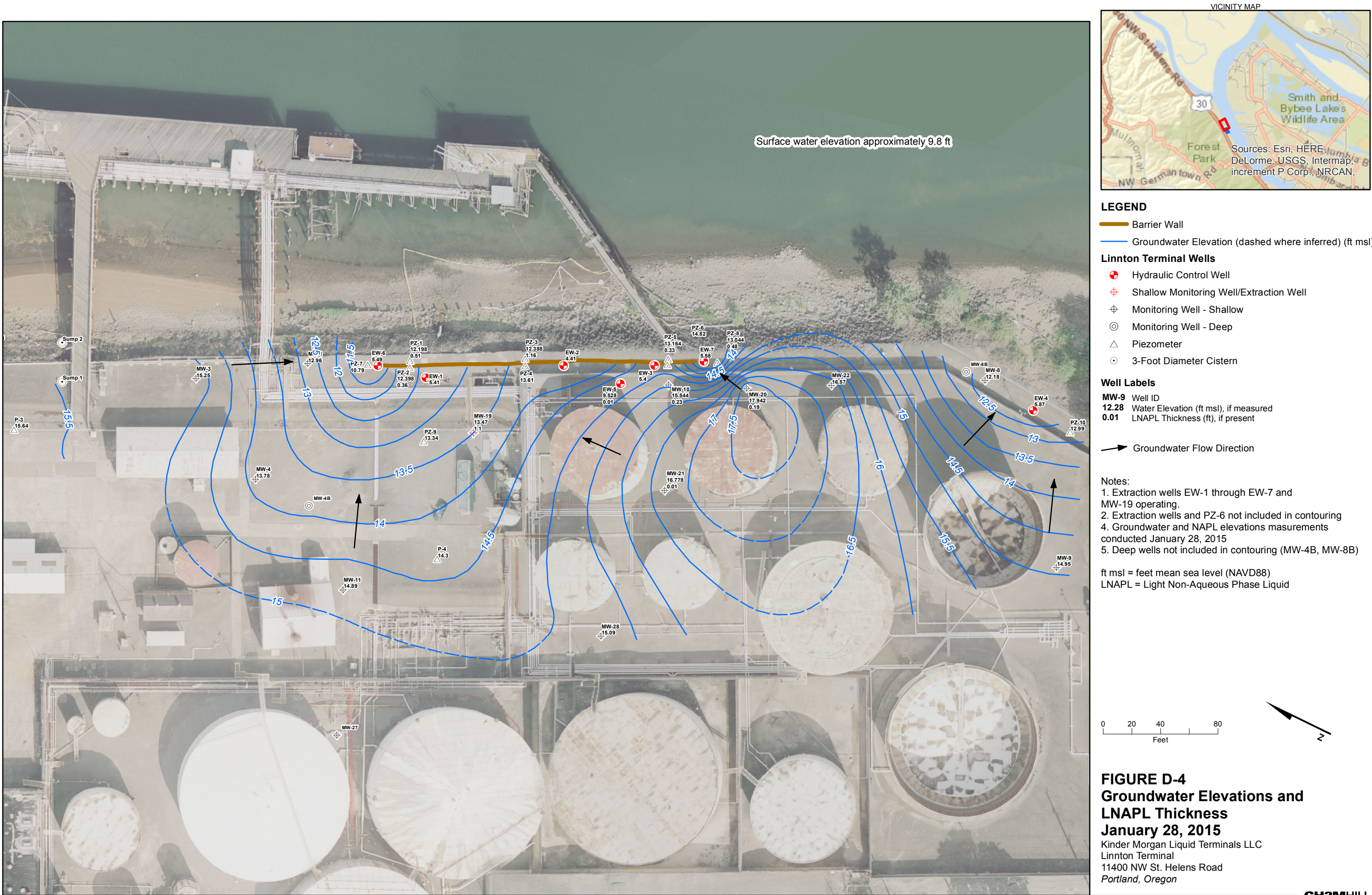*Kinder Morgan Liquids Terminals, Linnton Terminal*

FIGURE D-3
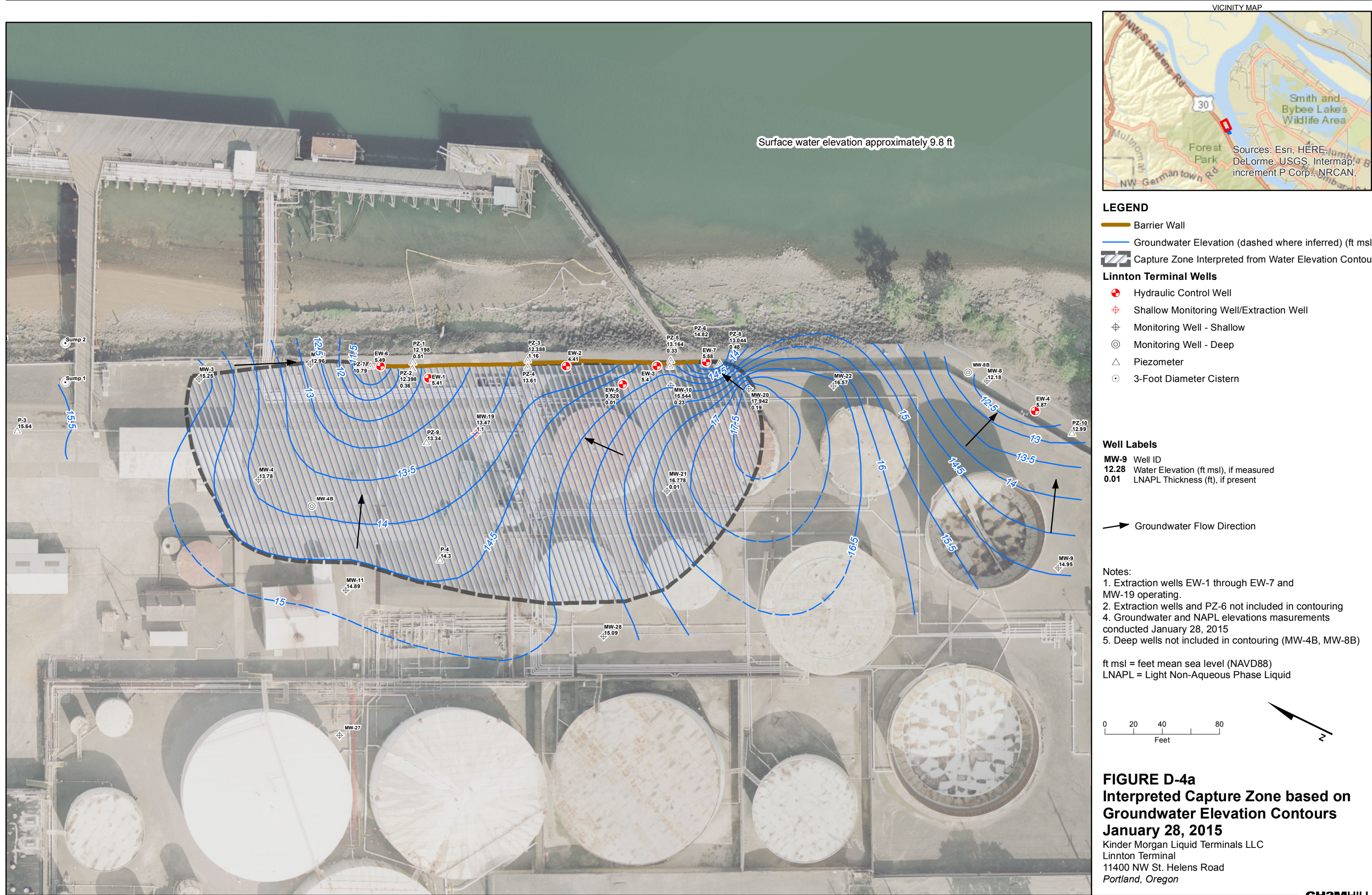Vertical Gradients
Kinder Morgan Liquid Terminals, Linnton Terminal

Surface water elevation approximately 9.8 ft

VICINITY MAP

Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN.

LEGEND

— Barrier Wall

— Groundwater Elevation (dashed where inferred) (ft msl)

Linnton Terminal Wells

⊕ Hydraulic Control Well

⊕ Shallow Monitoring Well/Extraction Well

⊕ Monitoring Well - Shallow

◎ Monitoring Well - Deep

△ Piezometer

⊙ 3-Foot Diameter Cistern

Well Labels

MW-9   Well ID
12.28   Water Elevation (ft msl), if measured
0.01   LNAPL Thickness (ft), if present

→ Groundwater Flow Direction

Notes:
1. Extraction wells EW-1 through EW-7 and MW-19 operating.
2. Extraction wells and PZ-6 not included in contouring
4. Groundwater and NAPL elevations masurements conducted January 28, 2015
5. Deep wells not included in contouring (MW-4B, MW-8B)

ft msl = feet mean sea level (NAVD88)
LNAPL = Light Non-Aqueous Phase Liquid

0 20 40 80
Feet

FIGURE D-4
Groundwater Elevations and
LNAPL Thickness
January 28, 2015
Kinder Morgan Liquid Terminals LLC
Linnton Terminal
11400 NW St. Helens Road
Portland, Oregon

CH2MHILL

VICINITY MAP

Sources: Esri, HERE, DeLorme, USGS, Intermap, increment P Corp., NRCAN.

Surface water elevation approximately 9.8 ft

LEGEND

▬▬ Barrier Wall

—— Groundwater Elevation (dashed where inferred) (ft msl)

▨ Capture Zone Interpreted from Water Elevation Contours

Linnton Terminal Wells

⊙ Hydraulic Control Well

⊕ Shallow Monitoring Well/Extraction Well

⊕ Monitoring Well - Shallow

◎ Monitoring Well - Deep

△ Piezometer

⊙ 3-Foot Diameter Cistern

Well Labels

MW-9 Well ID
12.28 Water Elevation (ft msl), if measured
0.01 LNAPL Thickness (ft), if present

→ Groundwater Flow Direction

Notes:
1. Extraction wells EW-1 through EW-7 and MW-19 operating.
2. Extraction wells and PZ-6 not included in contouring
4. Groundwater and NAPL elevations masurements conducted January 28, 2015
5. Deep wells not included in contouring (MW-4B, MW-8B)

ft msl = feet mean sea level (NAVD88)
LNAPL = Light Non-Aqueous Phase Liquid

0   20   40   80
Feet

FIGURE D-4a
Interpreted Capture Zone based on Groundwater Elevation Contours
January 28, 2015
Kinder Morgan Liquid Terminals LLC
Linnton Terminal
11400 NW St. Helens Road
Portland, Oregon

\\ROSA\PROJ\KINDERMORGAN\405127\GIS\MAPFILES\2015\GW_SCE_REVISION\FIGURED-4A_INTERPRETEDCAPTURE_V1.MXD JSAGER 8/20/2015 8:00:55 AM

CH2MHILL

Figure D-5
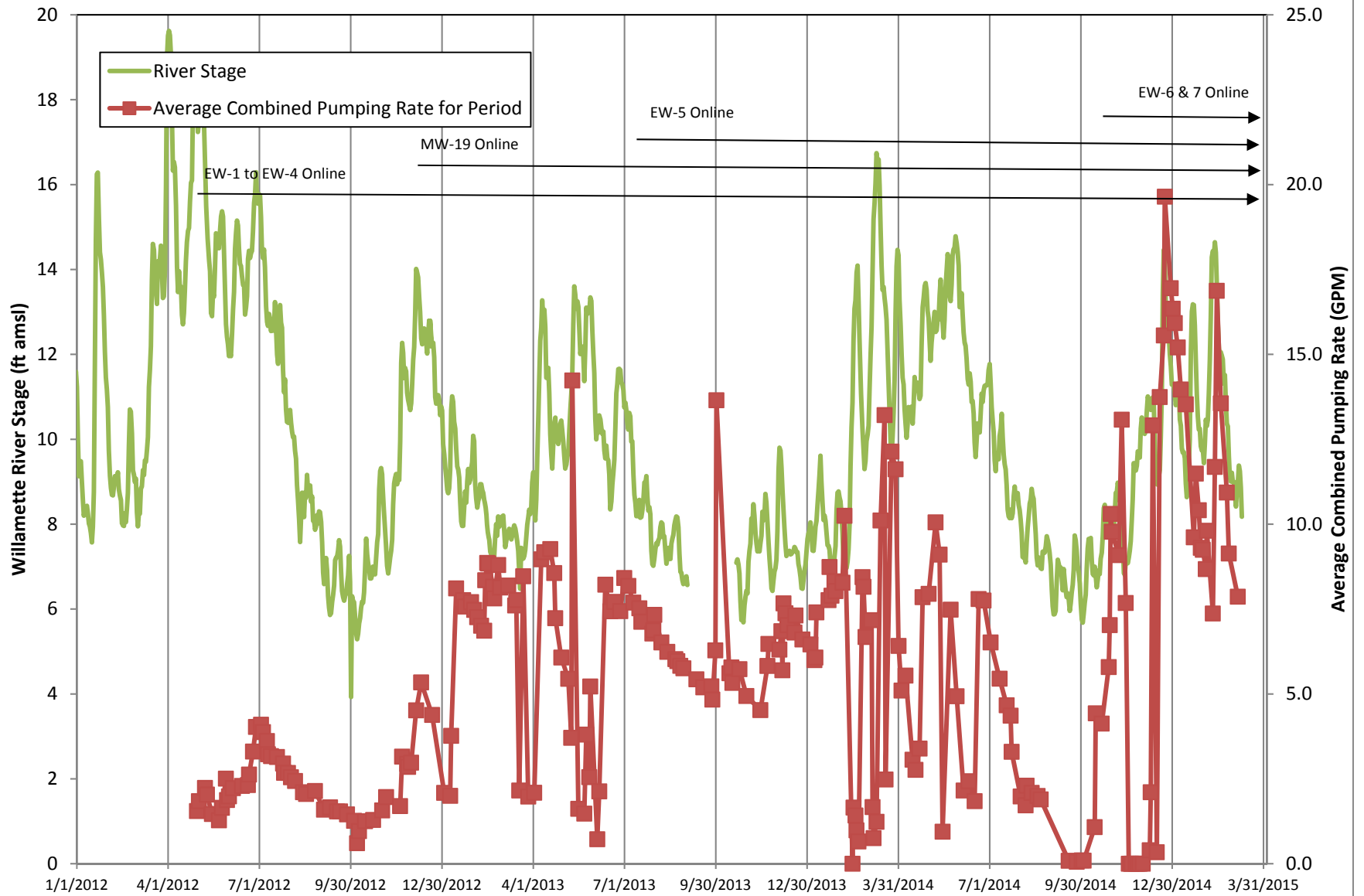**Flow Rates for Barrier Extraction System vs. River Stage**

FIGURE D-6a

Barrier Wall Vicinity - High-water Conditions

Analytical Model for Estimation of Steady-State Capture
Zones of Pumping Wells in Confined and Unconfined Aquifers
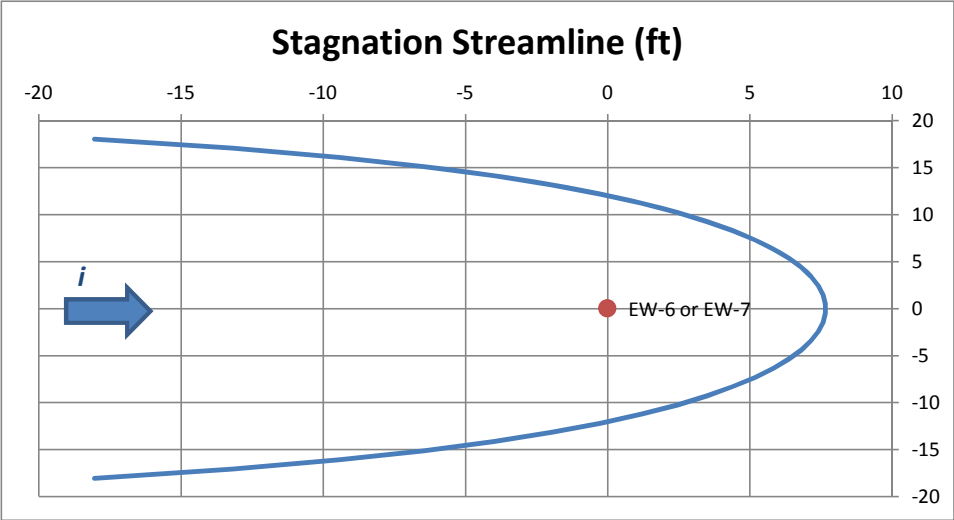
Kinder Morgan Liquid Terminals, Linnton Terminal

Unconfined Pumping Well in Uniform Flow at Infinite Time Stagnation Point			
Qw	Pumping rate	gpm	2
Qw	Pumping rate	ft^3/day	385.0267
Qo	Regional Flow Vector (Qo=T*i)	ft^2/day	8
K	Conductivity	ft/day	40
b	thickness	ft	20
i	gradient	ft/ft	0.01
Xstag	Stagnation Point downgradient from well	ft	8
yDIV	Half Capture Zone Width	ft	24

Input
Output

Reference:

Grubb, S. 1993. Analytical model for estimation of steady-state capture zones of
pumping wells in confined and unconfined aquifers. Ground Water. V. 31, pp. 27-
32.

2. Analytical Model

The assumptions for this model are as follows:

● The aquifer is homogeneous, isotropic, and infinite in horizontal extent.

● Uniform flow (steady-state) conditions prevail.

● A confined aquifer has a uniform transmissivity and no leakage through the upper or lower confining layers. An unconfined aquifer has a horizontal lower confining layer with no leakage, rainfall infiltration, or other vertical recharge. The effect of these assumptions is discussed later.

● Because the equations assume steady-state conditions, the storativity of a confined aquifer and the specific yield of an unconfined aquifer have been neglected. Hydrodynamic dispersion is also neglected.

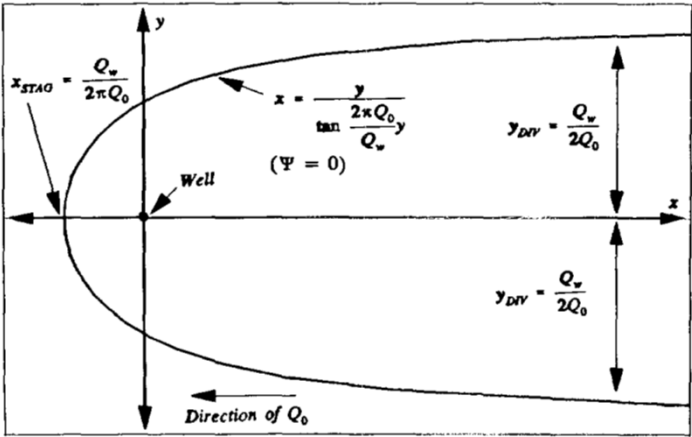● Dupuit assumption, i.e. vertical gradients are negligible.

Stagnation Streamline (ft)

$$x_{STAG} = \frac{Q_w}{2\pi Q_0}$$

$$x = \frac{y}{\tan \frac{2\pi Q_0 y}{Q_w}}$$

$$y_{DIV} = \frac{Q_w}{2Q_0}$$

$(\Psi = 0)$

Well

$$y_{DIV} = \frac{Q_w}{2Q_0}$$

Direction of Q_0

Fig. 1. Stagnation point, upgradient divide, and dividing stream-line at infinite time (steady state).

FIGURE D-6b

Barrier Wall Vicinity - Low-water Conditions

Analytical Model for Estimation of Steady-State Capture

Zones of Pumping Wells in Confined and Unconfined Aquifers

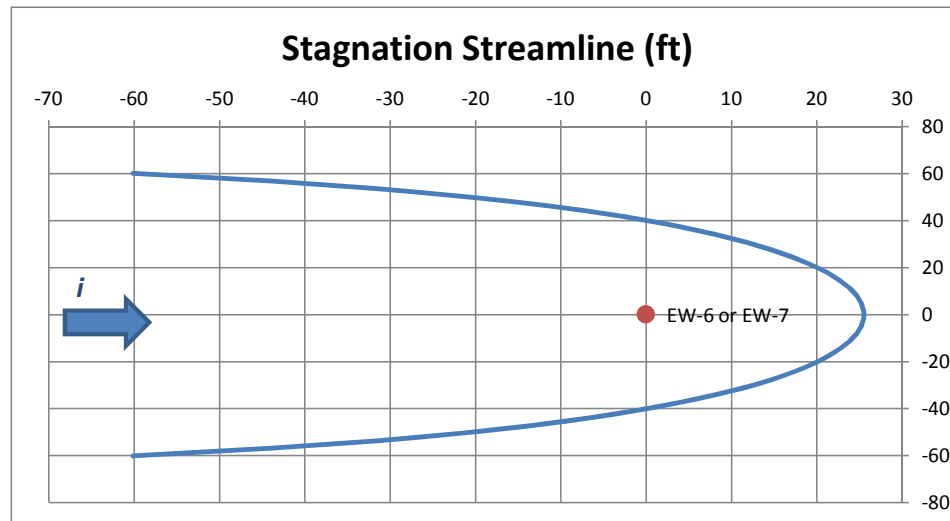*Kinder Morgan Liquid Terminals, Linnton Terminal*

Unconfined Pumping Well in Uniform Flow at Infinite Time Stagnation Point			
Qw	Pumping rate	gpm	1
Qw	Pumping rate	ft^3/day	192.5134
Qo	Regional Flow Vector (Qo=T*i)	ft^2/day	1.2
K	Conductivity	ft/day	4
b	thickness	ft	10
i	gradient	ft/ft	0.03
Xstag	Stagnation Point downgradient from well	ft	26
yDIV	Half Capture Zone Width	ft	80

Input
Output

Reference:

Grubb, S. 1993. Analytical model for estimation of steady-state capture zones of
pumping wells in confined and unconfined aquifers. Ground Water. V. 31, pp. 27-
32.

2. Analytical Model

The assumptions for this model are as follows:

● The aquifer is homogeneous, isotropic, and infinite in horizontal extent.

● Uniform flow (steady-state) conditions prevail.

● A confined aquifer has a uniform transmissivity and no leakage through the upper or lower confining layers. An unconfined aquifer has a horizontal lower confining layer with no leakage, rainfall infiltration, or other vertical recharge. The effect of these assumptions is discussed later.

● Because the equations assume steady-state conditions, the storativity of a confined aquifer and the specific yield of an unconfined aquifer have been neglected. Hydrodynamic dispersion is also neglected.

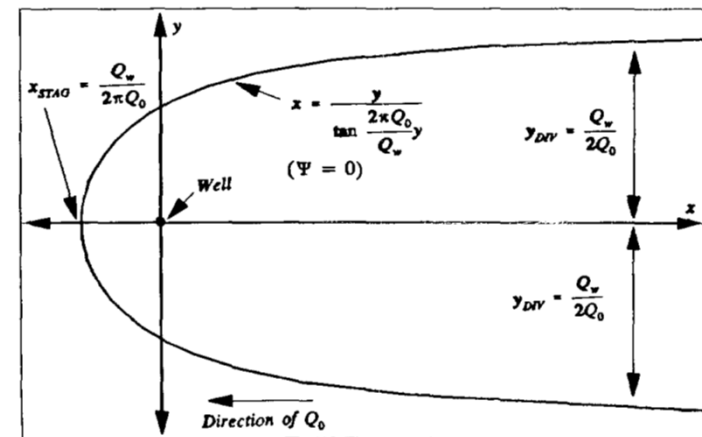● Dupuit assumption, i.e. vertical gradients are negligible.

Stagnation Streamline (ft)

Fig. 1. Stagnation point, upgradient divide, and dividing streamline at infinite time (steady state).

FIGURE D-6c

EW-4 Vicinity - High-water Conditions

Analytical Model for Estimation of Steady-State Capture

Zones of Pumping Wells in Confined and Unconfined Aquifers

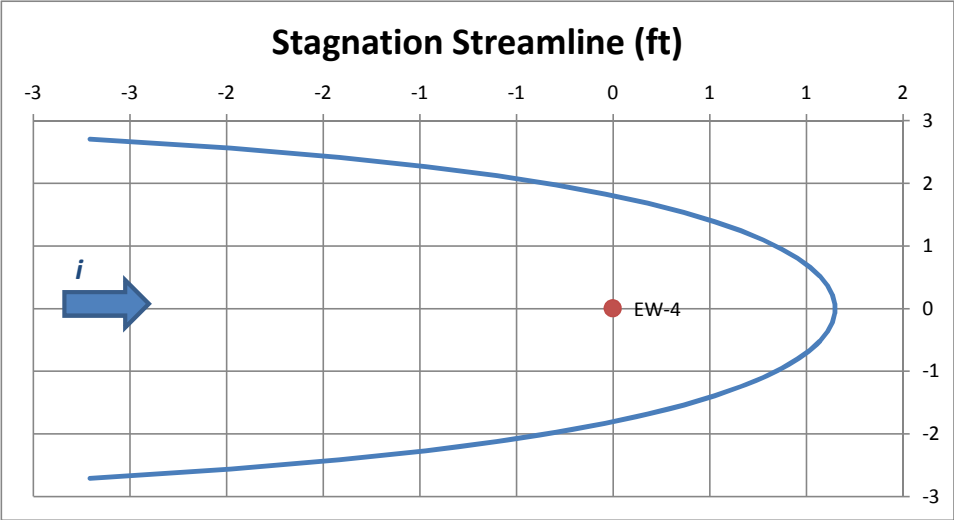*Kinder Morgan Liquid Terminals, Linnton Terminal*

Unconfined Pumping Well in Uniform Flow at Infinite Time Stagnation Point			
Qw	Pumping rate	gpm	0.6
Qw	Pumping rate	ft^3/day	115.508
Qo	Regional Flow Vector (Qo=T*i)	ft^2/day	16
K	Conductivity	ft/day	40
b	thickness	ft	20
i	gradient	ft/ft	0.02
Xstag	Stagnation Point downgradient from well	ft	1
yDIV	Half Capture Zone Width	ft	4

Input

Output

Reference:

Grubb, S. 1993. Analytical model for estimation of steady-state capture zones of
pumping wells in confined and unconfined aquifers. Ground Water. V. 31, pp. 27-
32.

2. Analytical Model

The assumptions for this model are as follows:

● The aquifer is homogeneous, isotropic, and infinite in horizontal extent.

● Uniform flow (steady-state) conditions prevail.

● A confined aquifer has a uniform transmissivity and no leakage through the upper or lower confining layers. An unconfined aquifer has a horizontal lower confining layer with no leakage, rainfall infiltration, or other vertical recharge. The effect of these assumptions is discussed later.

● Because the equations assume steady-state conditions, the storativity of a confined aquifer and the specific yield of an unconfined aquifer have been neglected. Hydrodynamic dispersion is also neglected.

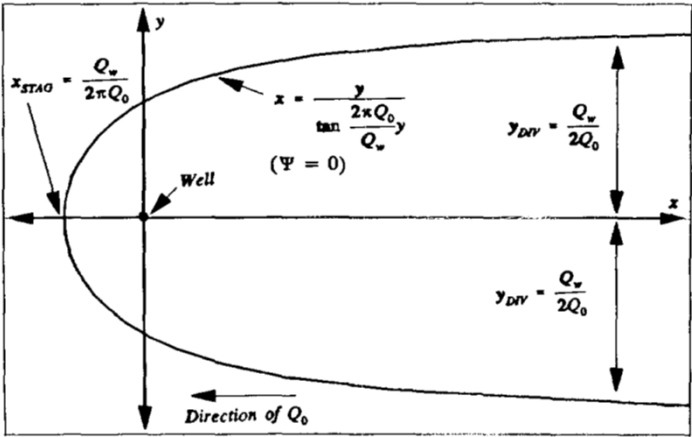● Dupuit assumption, i.e. vertical gradients are negligible.

Stagnation Streamline (ft)

$$x_{STAG} = \frac{Q_w}{2\pi Q_0}$$

$$x = \frac{y}{\tan\frac{2\pi Q_0 y}{Q_w}}$$

$$(\Psi = 0)$$

$$y_{DIV} = \frac{Q_w}{2Q_0}$$

$$y_{DIV} = \frac{Q_w}{2Q_0}$$

Direction of Q_0

Fig. 1. Stagnation point, upgradient divide, and dividing streamline at infinite time (steady state).

FIGURE D-6d

EW-4 Vicinity - Low-water Conditions

Analytical Model for Estimation of Steady-State Capture

Zones of Pumping Wells in Confined and Unconfined Aquifers
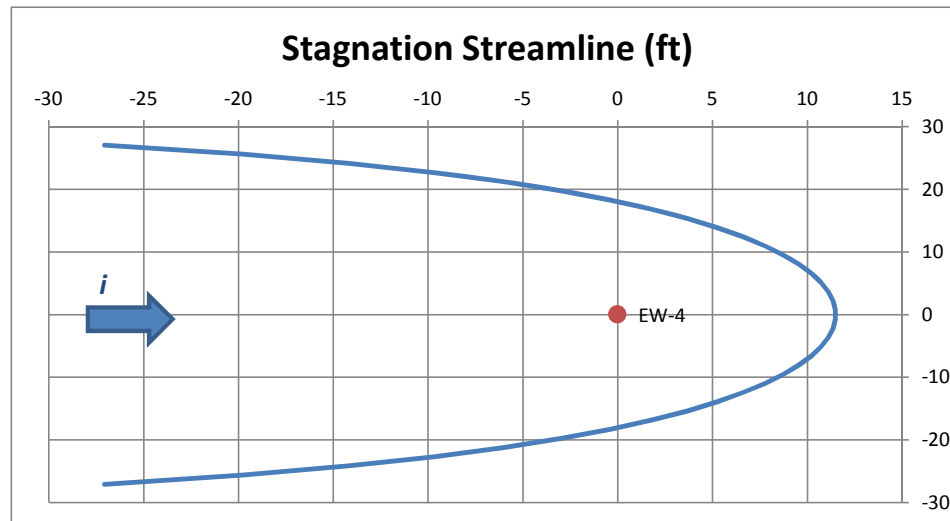
Kinder Morgan Liquid Terminals, Linnton Terminal

Unconfined Pumping Well in Uniform Flow at Infinite Time Stagnation Point			
Qw	Pumping rate	gpm	0.3
Qw	Pumping rate	ft^3/day	57.75401
Qo	Regional Flow Vector (Qo=T*i)	ft^2/day	0.8
K	Conductivity	ft/day	4
b	thickness	ft	10
i	gradient	ft/ft	0.02
Xstag	Stagnation Point downgradient from well	ft	11
yDIV	Half Capture Zone Width	ft	36

Input
Output

Reference:
 Grubb, S. 1993. Analytical model for estimation of steady-state capture zones of
 pumping wells in confined and unconfined aquifers. Ground Water. V. 31, pp. 27-
32.

Stagnation Streamline (ft)

2. Analytical Model

The assumptions for this model are as follows:

● The aquifer is homogeneous, isotropic, and infinite in horizontal extent.

● Uniform flow (steady-state) conditions prevail.

● A confined aquifer has a uniform transmissivity and no leakage through the upper or lower confining layers. An unconfined aquifer has a horizontal lower confining layer with no leakage, rainfall infiltration, or other vertical recharge. The effect of these assumptions is discussed later.

● Because the equations assume steady-state conditions, the storativity of a confined aquifer and the specific yield of an unconfined aquifer have been neglected. Hydrodynamic dispersion is also neglected.

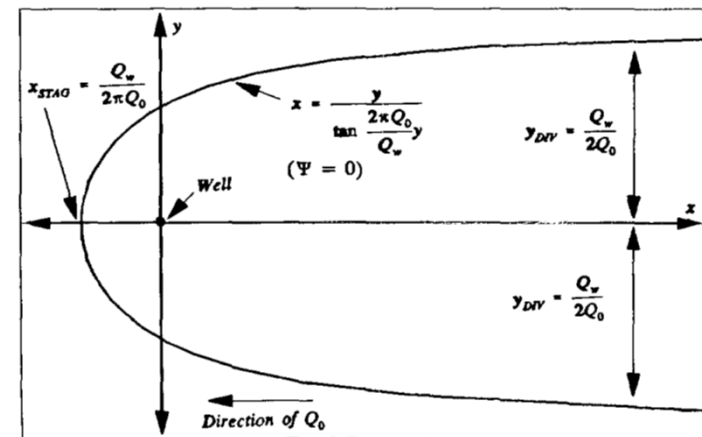● Dupuit assumption, i.e. vertical gradients are negligible.

Fig. 1. Stagnation point, upgradient divide, and dividing streamline at infinite time (steady state).

FIGURE D-7
Interpreted Capture based on Analytical Calculations and Water Level Contours
Kinder Morgan Liquid Terminals LLC
Linnton Terminal
11400 NW St. Helens Road
Portland, Oregon

CH2MHILL